Testing laser-based sensors for continuous *in situ* monitoring of suspended sediment in the Colorado River, Arizona

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Abstract High-resolution monitoring of sand mass balance in the Colorado River below Glen Canyon Dam, Arizona, USA, is needed for environmental management. In the Grand Canyon, frequent collection of suspended-sediment samples from cableways is logistically complicated, costly and provides limited spatial and temporal resolution. *In situ* laser sensors were tested in the Colorado River as an alternative method for monitoring the river's suspended transport. LISST data were collected at a fixed-depth, near-shore site while isokinetic measurements were simultaneously made from a nearby cableway. Diurnal variations in LISST grain size and concentration data compared well with depth-integrated, cross-section data. The LISST was also successfully used to electronically trigger an ISCO 6712 pump sampler to provide continuous monitoring during periods when suspended concentrations exceeded the LISST's measurement range. Initial results indicate that the LISST can provide useful high-resolution suspended-sediment data within the Colorado River, when optics are maintained on a weekly basis.

Key words Colorado River; environmental monitoring; LISST; suspended-sediment transport

INTRODUCTION

Closure of the Glen Canyon Dam in 1963 (Fig. 1) resulted in an immediate and drastic reduction of the Colorado River ecosystem's fine-sediment supply, as well as substantial changes in the river's seasonal transport behaviour (Topping *et al.*, 2000a, 2000b). Today, the annual fine-sediment supply below the dam is about 10% of the pre-dam supply and is delivered to the ecosystem mostly by the Paria and Little Colorado rivers (Fig. 1). Downstream sand inputs are fine (median size ~115 μm), while the dam's operation has increased the daily median flow of the Colorado River through the Grand Canyon by about a factor or two. Together, these factors cause erosion of existing sand bars and force rapid export of new sand inputs under most current dam operations (Rubin *et al.*, 2002). The sand bars represent the channel-storage term of the ecosystem's fine-sediment mass balance and restoration of eroded sand bars is a primary objective of an ongoing adaptive environmental assessment and management programme.

Owing to the ecosystem's sand-supply limited condition, intensive monitoring of fine sediment below Glen Canyon Dam is a critical requirement for successful

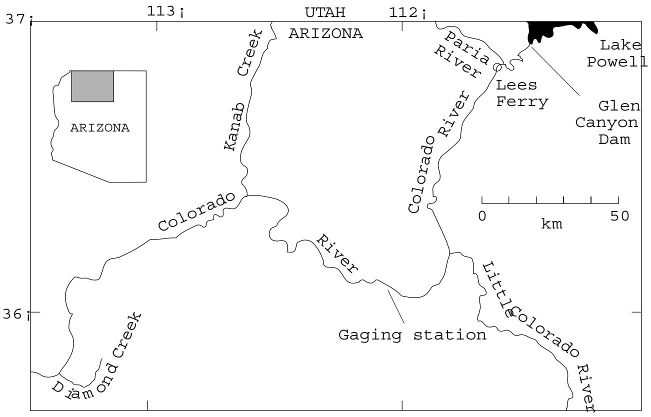

Fig. 1 Map of the Colorado River downstream from Glen Canyon Dam.

environmental management. One major objective of the monitoring programme is to identify key periods when the ecosystem's sand supply is sufficiently enriched for artificial floods to rebuild sand bars. Typically, this is done by estimating the system-wide sand mass balance between influx from tributaries and export from the Grand Canyon. Daily measurements of suspended transport using isokinetic samplers from cableways are currently required to estimate monthly-to-seasonal sand flux below the dam. Collection of these samples is logistically complicated, costly, and provides limited spatial and temporal resolution with respect to the variability of sand transport. The objective of this paper is to evaluate the potential for using LISST technology to increase the spatial and temporal resolution of suspended-transport monitoring in the Colorado River.

RESULTS AND DISCUSSION

Initial point data collected at a fixed-depth, near-shore site were obtained by averaging 16 measurements at 2-min intervals during a 24-h deployment starting at 23:00 h GMT on 19 July, 2001. These data were collected using a LISST-100 "Type-B" sensor (Laser In-Situ Scattering and Transmissometry) manufactured by [†]Sequoia Scientific, Inc. in Bellevue, Washington, USA. The Type-B is a laser-diffraction based sensor designed to detect suspended particles over a size range of 1.3–250 µm. An additional description of this technology is reported by Agrawal & Pottsmith (2001). The LISST-100B used in July 2001, was previously evaluated under laboratory and field conditions and its performance is reported by Gartner *et al.* (2001).

The 720 LISST point measurements collected at the Grand Canyon gauge in July 2001, compare well with cross-sectional integrated suspended-sand and silt and clay data collected at a cableway near the test site using a D-77 isokinetic bag sampler (Fig. 2). During the July 2001 test, fluctuating releases from Glen Canyon Dam ranged from about 320–480 m^3 s^{-1} (typical diurnal pattern of discharge related to hydropower generation at the dam). In addition to accurately tracking the sand concentration, the LISST-100B also recorded the physically-expected increase in sand-concentration variance as flow increased, with peak values ranging from 50 to 140 mg l^{-1} (Fig. 2(a)). Concentrations of silt and clay obtained by the LISST-100B were less variable by a

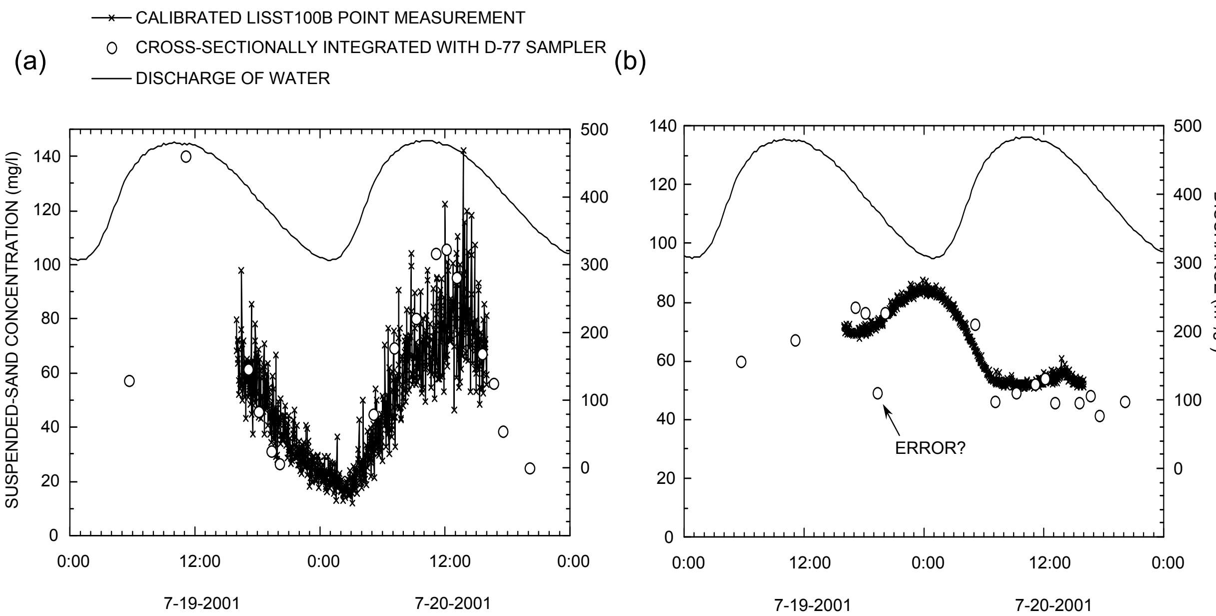

Fig. 2 (a) Comparison of sand concentrations and (b) silt and clay concentrations measured at the Grand Canyon gauge using LISST-100B and a D-77 bag sampler during the one-day July 2001 test. Discharge data are from the Grand Canyon gauge.

factor of nine, ranging from about 50 to 60 mg l^{-1} during the diurnal peak (Fig. 2(b)). This is likely the result of a high degree of turbulence at the test site that keeps the fines well mixed and sampled more consistently, relative to sand-sized particles.

A second field test was conducted from 22 September, 2001 to 8 February, 2002, to explore performance characteristics of both the LISST-100B and a LISST-25 during longer, continuous deployments required for long-term monitoring. Both the LISST-100B and the LISST-25 measure only the volumetric concentration and grain size of suspended particles. However, mass concentration can be estimated by the user once a suitable density conversion is gravimetrically determined. The LISST-25 tested has a size range similar to the LISST-100B, however, the LISST-25 provides only a sauter mean diameter (the ratio of particle surface area to volume) rather than a size distribution, as provided by the LISST-100B. During autumn 2001, the LISST-100B was fitted with a path-reduction module (PRM) to expand the instrument's concentration range by almost a factor of four (optical path of 5 cm reduced to 1 cm). Although path reduction does allow for higher-concentration measurements (by reducing the sample volume and related number of particles that attenuate laser transmission), the optical accessory used for testing turned out to be flawed and altered the raw data in ways that were not trivial to resolve. The PRM's influence was most pronounced on scattering related to the sand-sized particles (inner rings of the detector). It is therefore essential that each PRM used with LISST be tested and carefully evaluated prior to field deployment. In contrast to the LISST-100B with the PRM, the LISST-25 (fixed optical path of 2.5 cm) measured higher concentrations of suspended sediment with no discernable complications over the 4-month long test. Despite complications introduced by the faulty PRM, the 10–18 January 2002 concentration data obtained from the LISST-100B also compared well with cableway samples for sand (Fig. 3(a)) and silt and clay (Fig. 3(b)) collected with the D-77 bag sampler.

Suspended-sediment grain size is an important component of the Grand Canyon monitoring protocol (see section below). For the July 2001 test, the LISST-100B provided median grain size data for sand that closely matched sand sizes obtained using the D-77 sampler (Fig. 4(a)). Grain-size data for sand from the January 2002 test also compared well with the D-77 data (Fig. 4(b)). A 5-week deployment of the

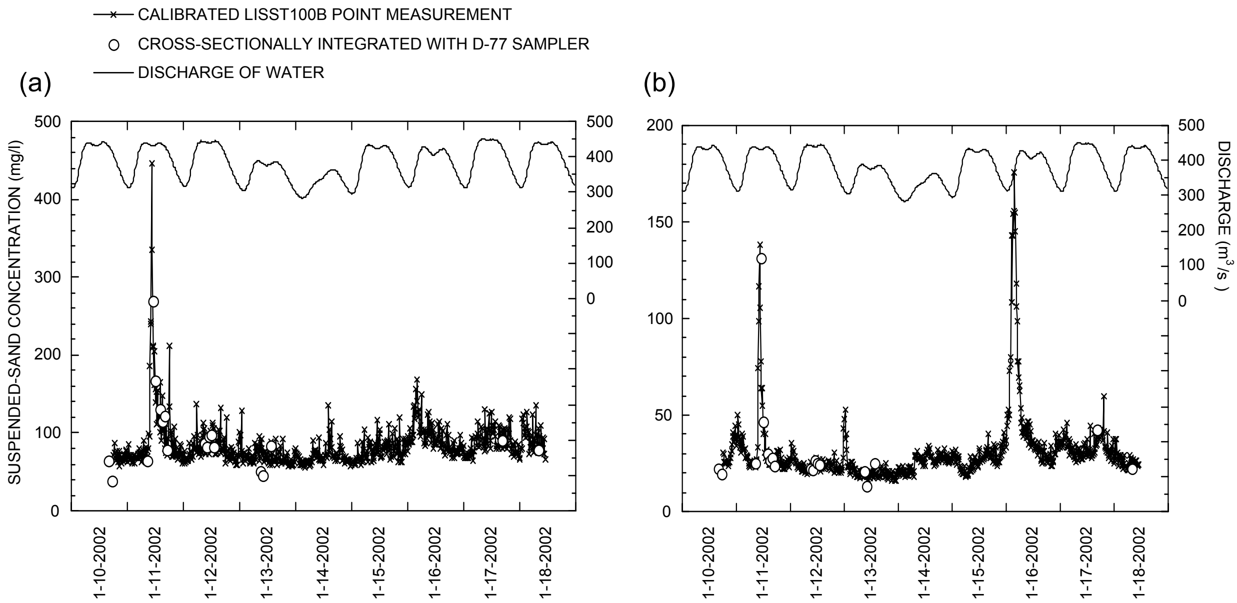

Fig. 3 (a) Comparison of sand concentrations and (b) silt & clay concentrations measured at the Grand Canyon gauge using LISST-100B (with 80% PRM) and the D-77 bag sampler during the multi-day January 2002 test. Discharge data are from the Grand Canyon gauge.

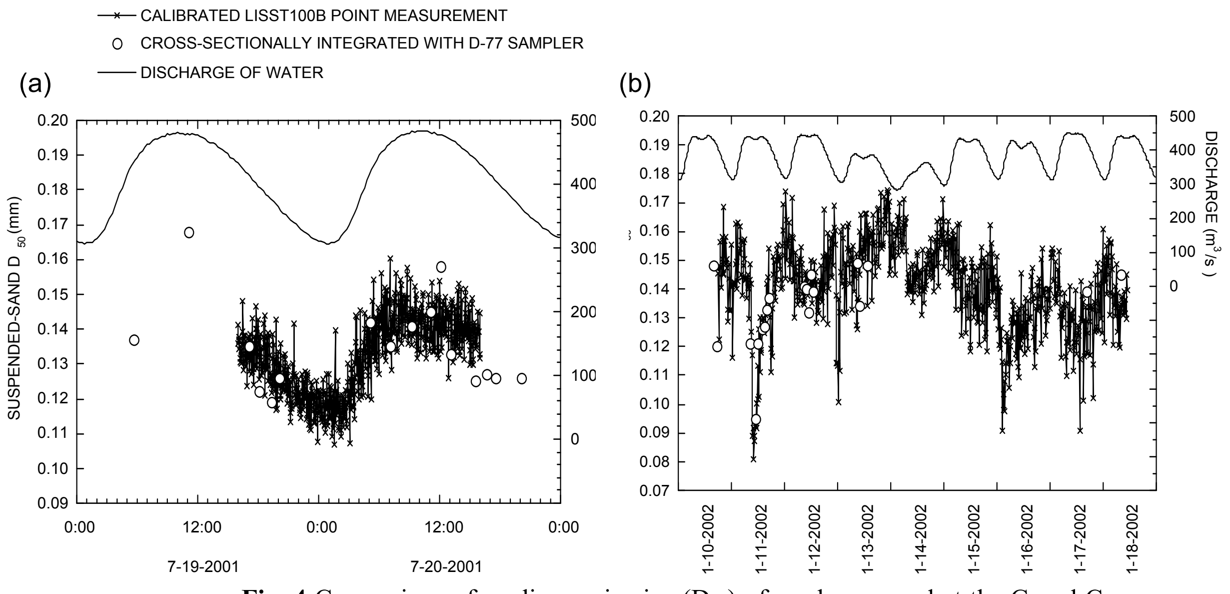

Fig. 4 Comparison of median grain size (D_{50}) of sand measured at the Grand Canyon gauge using LISST-100B and the D-77 bag sampler during (a) the one-day July 2001 test, and (b) the multi-day January 2002 test. Discharge data are from the Grand Canyon gauge.

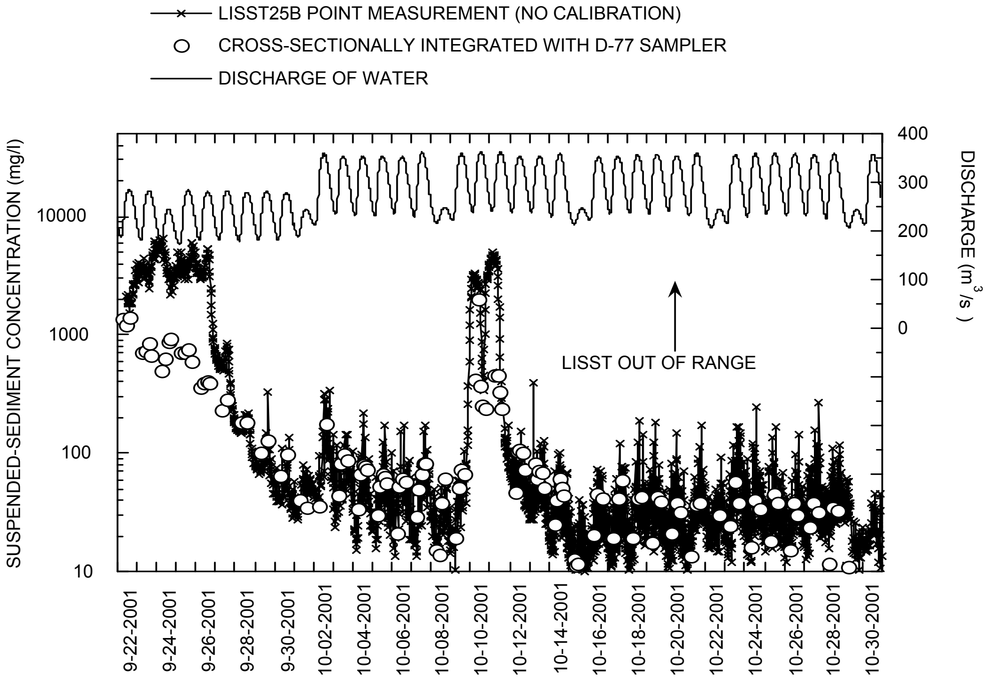

Fig. 5 Comparison of total suspended-sediment concentrations (1.3–250 μm) measured at the Grand Canyon gauge using LISST-25 and D-77 bag sampler during the multi-week autumn 2001 test. Discharge data are from the Grand Canyon gauge.

LISST-25 provided the most compelling results as to how well these optical instruments perform during continuous deployments (Fig. 5). Even during September 2001, when the LISST-25 was technically out-of-range (laser transmission <20%), these non-calibrated data generally tracked the D-77 samples.

Although the non-calibrated test results from the LISST-25 compare well with cross-section measurements for total concentration (once the volume to mass conversion was made, Fig. 5), the LISST-25 provides no possibility for separating measurements of sand from finer particles (the sand split is made at 63 μm). This LISST-25 limitation presents a serious shortcoming for monitoring deployments where sand transport is of primary concern, such as the Colorado River. During the 2002 field tests, the manufacturer developed a LISST-25 firmware upgrade to segregate sand from finer-particle data and made it available for testing (L25X). The July 2002 sand concentrations derived from the L25X compared very well with cableway sample data ($R^2 = 0.86$).

During relatively brief periods when the river below the dam becomes greatly enriched with fine sediment from tributary inputs, LISST overestimates the concentration of fine particles (Fig. 5). Such errors occur owing to multiple scattering associated with abundant fines, a phenomenon that tends to bias counts on the outer rings of the detector array. Multiple scattering has been identified as a significant source of concentration error when laser transmission falls below 20% (Agrawal & Pottsmith, 2001). To monitor such periods, a method was devised that allowed the LISST to electronically control a programmable automated pumping sampler. The protocol is as follows: when LISST measures laser transmission below the 20% threshold, the instrument electronically enables the user-defined programme of its counterpart ISCO 6712 sampler. Once activated, point samples are then collected from an intake located near the LISST deployment at pre-defined intervals. Automated sampling continues until either the laser transmission threshold is again exceeded, or the supply of sample bottles is exhausted. The ability of the LISST to control the pump sampler ensures that additional concentration and grain-size data are collected during periods when multiple scattering errors are most likely to occur. Low-transmission periods are of obvious interest since they represent times of greatest sediment enrichment, as well as peak export from Grand Canyon. This protocol also allows for the 24 sample bottles to be conserved in the sampler's carousel—a critical factor at remote measurement locations in Grand Canyon where daily maintenance is not possible.

Monitoring channel-bed sediment supply using LISST and β

Previous work has shown that suspended-sediment concentration and grain-size data can be used to calculate grain size of sediment on the bed upstream (Rubin & Topping, 2001). A dimensionless measure of grain size of sediment on the bed, β, is defined as:

$$\beta = \frac{D_b}{D_{bm}} \tag{1}$$

where D_b is the median grain diameter of bed sediment at an instant in time and D_{bm} is the average of a sequence of median diameters at the same location at different times. β is thus a measure of the relative coarseness of sediment on the bed. Expressed in terms of the LISST-observable variables (concentration and grain size of suspended sediment), β is given by:

$$\beta = \left(\frac{C}{C_m}\right)^{-0.1} \left(\frac{D_s}{D_{sm}}\right)^{0.2} \tag{2}$$

where C and D_s are the concentration and median diameter of suspended sediment at an instant in time, and C_m and D_{sm} are their time respective averages through time. In equation (2), the exponent of the concentration ratio is negative, whereas the exponent of the grain-size ratio is positive. An increase in suspended-sediment grain size is accompanied by a decrease in concentration, indicating a coarsening of the bed upstream. Suspended-sediment data from the 1996 controlled flood released from Glen Canyon Dam (a flow treatment in which a fixed sand supply was exposed to a constant discharge of 1275 m^3 s^{-1} for 7 days) reveals rapidly increasing values of β during the first 72 h of that experiment (indicating bed winnowing). The β values derived from the 1996 beach-building experiment provide an example of how LISST data might be monitored in real time during artificial floods to identify the onset of sand depletion during future sand-bar restoration tests. By this means, flood duration might be optimized.

Because the β value, derived by the above method, is a surrogate for how enriched a river segment is in fine sediment, it can thus provide an indirect and rapid reach-integrated measure of a river's fine-sediment mass balance (in non-armoured conditions). For example, within a period of less than 24 h on 11 January 2002, the LISST-100B recorded about a factor of seven increase in sand concentration and about a 50% decrease in median grain size of sand (β abruptly decreased). This change in sand-transport occurred in direct response to enrichment of the river's sediment supply following tributary inputs (Figs 3(a) and 4(b)) rather than simply a diurnal change in discharge. Results such as these suggest that LISST data will be suitable for calculating β at higher spatial and temporal resolutions than those that are presently obtained using cableway sampling methods. A similar monitoring approach may also have utility where high flows are released from dams to accomplish spawning habitat restoration and maintenance through evacuation of sand and silt from gravel-bed interstices. This approach using β may also be applied to other sediment transport environments.

CONCLUSIONS

Overall, the results of these initial field tests indicate that, with frequent maintenance of optics and when used in combination with automated pumping samplers, LISST can support continuous suspended-sediment monitoring in the Colorado River. However, because both the LISST and the pump sampler provide only point data, it is still necessary to obtain depth-integrated, cross-section measurements using isokinetic samplers frequently enough to develop reliable box coefficients.

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[†]Any use of trade, product, or firm names is for descriptive purposes only and does not constitute endorsement by the US Geological Survey.

REFERENCES

Agrawal, Y. & Pottsmith, C. (2001) Laser sensors for monitoring sediments: capabilities and limitations, a survey. *Proc. Seventh Fed. Inter. Sed. Conf.* (III), 144–151.

Gartner, J. W., Cheng, R. T., Wang, P. & Richter, K. (2001) Laboratory and field evaluations of the LISST-100 instrument for suspended particle size determinations. *Marine Geol.* **175**, 199–219.

Rubin, D. M. & Topping, D. J. (2001) Quantifying the relative importance of flow regulation and grain size regulation of suspended sediment transport (α) and tracking changes in grain size of bed sediment (β). *Water Resour. Res.* **37**(1), 133–146.

Rubin, D. M., Topping, D. J., Schmidt, J. C., Hazel, J., Kaplinski, M. & Melis, T. S. (2002) Recent sediment studies refute Glen Canyon Dam hypothesis. *Eos* **83**(25), 273–278.

Topping, D. J., Rubin, D. M. & Vierra, L. E., Jr (2000a) Colorado River sediment transport, 1. Natural sediment supply limitation and the influence of Glen Canyon Dam. *Water Resour. Res.* **36**(2), 515–542.

Topping, D. J., Rubin, D. M., Nelson, J. M., Kinsel, P. J. III & Corson, I. C. (2000b) Colorado River sediment transport, 2. Systematic bed-elevation and grain-size effects of sand supply limitation. *Water Resour. Res.* **36**(2), 543–570.